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THE DIFFUSION OF OXYGEN THROUGH STORED COAL

BY

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THE DIFFUSION OF OXYGEN THROUGH STORED COAL.

By S. H. Katz.

INTRODUCTION.

This study of the rate of diffusion of oxygen through coal forms part of an extended investigation of the conditions affecting deterioration and spontaneous combustion of stored coal that has been undertaken by the Bureau of Mines, under the direction of Horace C. Porter, formerly chemical engineer of the bureau.

The experiments herein described were made in the attempt to determine the effects of the size of the coal pieces and the proportion of voids in a coal pile on the rate at which oxygen can be brought by diffusion from the air around the pile to the coal within, the purpose being to discover the bearing of diffusion on the rate of spontaneous heating within the pile.

The fact that coal oxidizes at ordinary temperatures has been well established by many investigators.[a] Winmill measured the heat evolved during such oxidation and found that per unit of oxygen consumed it is nearly as great as that produced by combustion at high temperatures. Combination of oxygen with coal during storage causes a loss in heating value of the coal. Porter and Ovitz[b] have shown that coal from New River, W. Va., exposed to the air out of doors, at Key West, Fla., for two years, lost 1.85 per cent of its calorific value. At Portsmouth, N. H., a comparative lot of the same coal lost 0.77 per cent of its calorific value in two years. Industrial and economic conditions often necessitate the storage of large quantities of coal, so that the loss of fuel values throughout the country from this cause is considerable.

As spontaneous combustion frequently occurs when bituminous coal is stored in large quantities for any length of time,[c] there is

[a] Richters, E., Über die Veränderungen welche die Steinkohle beim Lagern an der Luft erleiden: Dingl. Poly. Jour., vol. 195, 1870, 315–331 and 449–458; Porter, H. C., and Ralston, O. C., A study of the oxidation of coal: Tech. Paper 65, Bureau of Mines, 1914, 30 pp.; Winmill, T. F., The absorption of oxygen by coal: Coll. Guard., vol. 108, 1914, pp. 564–567; Porter, H. C., and Ovitz, F. K., Deterioration in the heating value of coal during storage: Bull. 136, Bureau of Mines, 1917, 38 pp.

[b] Porter, H. C., and Ovitz, F. K., Deterioration and spontaneous heating of coal in storage: Tech. Paper 16, Bureau of Mines, 1912, 14 pp.

[c] Porter, H. C., and Ovitz, F. K., work quoted; Crapo, G. R., Land storage of bituminous coal; the ever present factor of spontaneous combustion; and a few facts and suggestions in connection with same: Jour. Am. Soc. Naval Eng., vol. 27, 1915, pp. 663–674.

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need of more information about the causes of spontaneous combustion, and the present work has a bearing on this problem also.

When coal is stored in the air, the diminution of oxygen in the air within the mass, through oxidation of the coal, causes oxygen from the outside air to enter by both convection and diffusion, thus providing the means for further oxidation. The amount of oxidation from diffusion while air is entering by convection will vary with the magnitude of the convection. Hence the amount of oxidation that may be attributed to either convection or diffusion will differ greatly with conditions. This paper, however, considers only the effects of diffusion.

PLAN OF THE EXPERIMENTS.

DESCRIPTION OF APPARATUS.

The apparatus used in the investigation is pictured in Plate I. Details are shown in figures 1, 2, 3, and 4. In Plate I, *a* indicates a Kipp generator for the hydrogen used to remove the oxygen by combustion; *b* and *c* represent two 20-liter bottles for collecting and measuring the hydrogen; *d* is a bubbler for showing the rate of flow of the hydrogen; *e* is the lower and *f* the upper separable sections of the chamber in which the diffusion took place.

The chamber may be considered divided into three compartments, placed one above the other. Details of the lower compartment and of the coal compartment are given in figure 1, in which a_1, a_2, and a_3 represent tubes opening into the interior, a_1 and a_2 being closed with rubber stoppers. Through a_3 was run a capillary tube *b*, from the center of the lower compartment to the gas-sampling apparatus. The coal was supported by a stiff steel-wire net, *d*, of $\frac{1}{8}$-inch mesh, resting on the lugs *c* and *c*. When coal finer than $\frac{1}{8}$-inch mesh was used a fine wire gauze was laid over the net.

The circular reservoir *e* was built around the coal compartment. Near the bottom of the reservoir the rod *i* bent into a circle was solidly fixed by means of the rods *k* and *j*, which were placed at intervals. The reservoir was kept two-thirds full. When the upper compartment was in place the water seal separated the gas inside from the air outside. On top of this compartment were the five tubes k_1, k_2, k_3, k_4, and k_5 (fig. 2) leading to the interior. Tube k_1 was closed by a rubber stopper; tube k_2 was joined to the stop cock *o;* through tube k_3 passed a glass tube with cock *j* for conducting the hydrogen. Inside the compartment this tube was joined to an absorption tube *l* (fig. 3) filled with glass wool to prevent backfiring. The hydrogen was led further to the silica nozzle m_3 at the center of the compartment. The jet of hydrogen was ignited by the electrically heated platinum spiral *n*. A glass window (Pl. I) allowed the progress of

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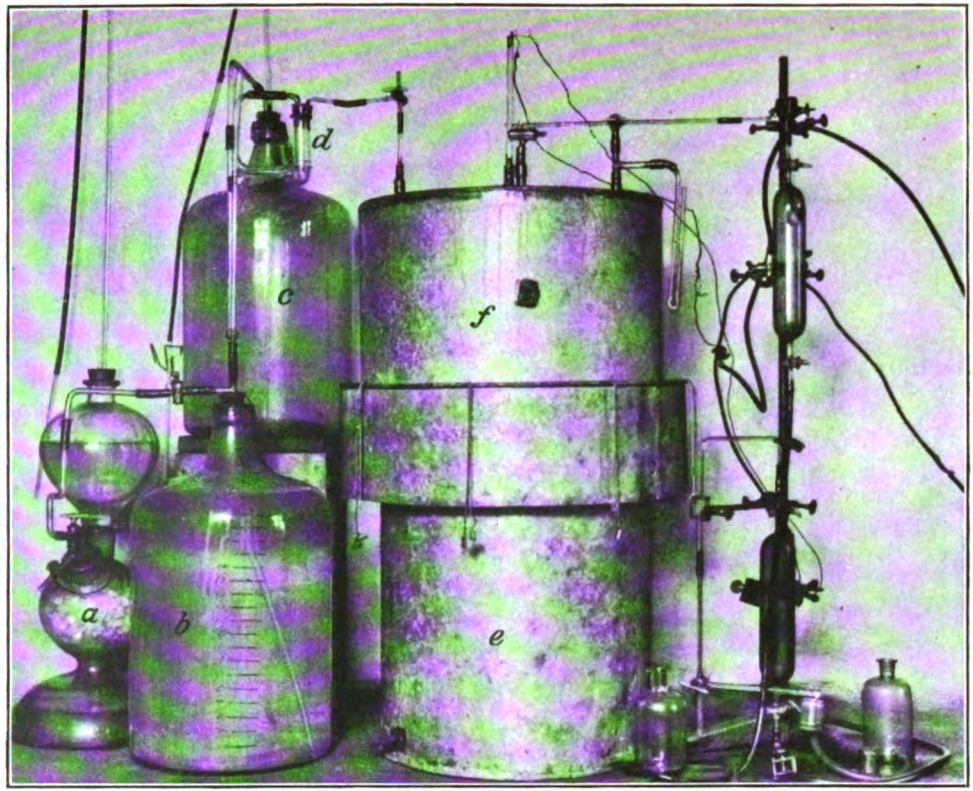

APPARATUS USED IN EXPERIMENTS.

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combustion to be watched. The capillary tube c (fig. 3) for taking gas samples led from the center of the compartment through the tube k_4. Also at k_4 the tube d connected the water manometer e with the interior of the apparatus. A solution of equal parts of glycerin and water was used in the gas-sample tubes g and the leveling bottles h (figs. 1 and 3) to displace the gas when procuring samples.

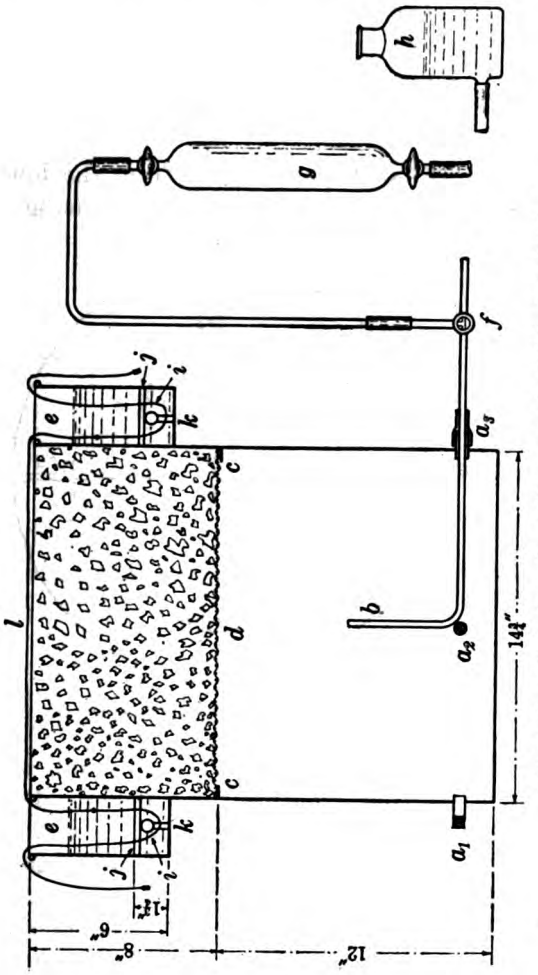

FIGURE 1.—Vertical section of lower part of diffusion chamber.

While the oxygen was being burned from the upper compartment the coal was covered with a diaphragm of "rubberized" cloth l (fig. 1), shown in detail in figure 4. Diffusion was started by removing the diaphragm through pulling proper strings. These strings were tied at the reinforced holes shown in figure 4 and were arranged as shown in the figures. In use the diaphragm was placed over the coal compartment and the strings brought down and under the circular

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rod *i*, figure 1, and up and over the outside rim of the reservoir. By pulling the proper strings the diaphragm could be stretched tightly over the coal with its edge on all sides dipping below the surface of the water and forming a practically gas-tight covering. When the upper compartment was in position, the diaphragm could be removed by pulling other strings. Both edges of the reservoir were finished to allow the strings and diaphragm to slide readily. As assembled for experiment the upper and the lower compartments of the apparatus contained very nearly equal volumes.

DATA AND CALCULATIONS.

Samples of gas were taken periodically from the lower and the upper compartment and analyzed to indicate the change of concen-

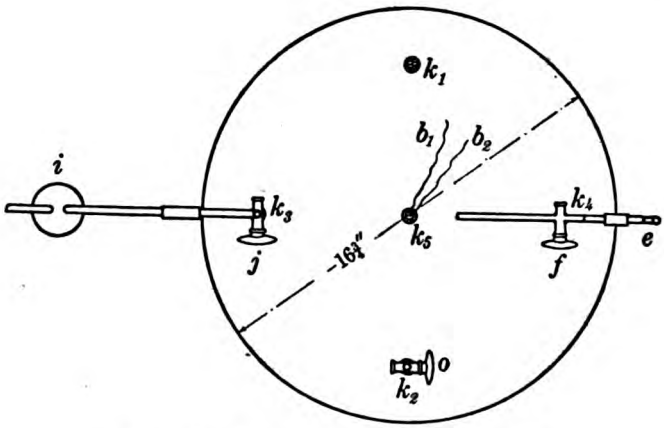

FIGURE 2.—Plan of top of diffusion chamber.

tration of oxygen. From the analytical results and the time the samples were taken the time required for a definite degree of diffusion to take place was calculated.

The size of the particles, the percentage of voids, and the depth of coal in the coal compartment were varied. Comparison of the calculated values of time for diffusion, which were obtained with the different conditions in the coal, showed the effect of these varying conditions on the rate of diffusion through the coal.

PERTINENT FACTS BROUGHT OUT BY THE INVESTIGATIONS.

The investigations have shown the following facts:

(1) That in itself the size of the coal particles has no effect on the rate at which oxygen diffuses through a mass of broken coal.

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(2) That, with masses of coal having different proportions of voids, the time required for a definite amount of diffusion increases in about inverse proportion to the percentage of voids.

From this information the following principles of practical import in reducing deterioration of stored coal may be deduced:

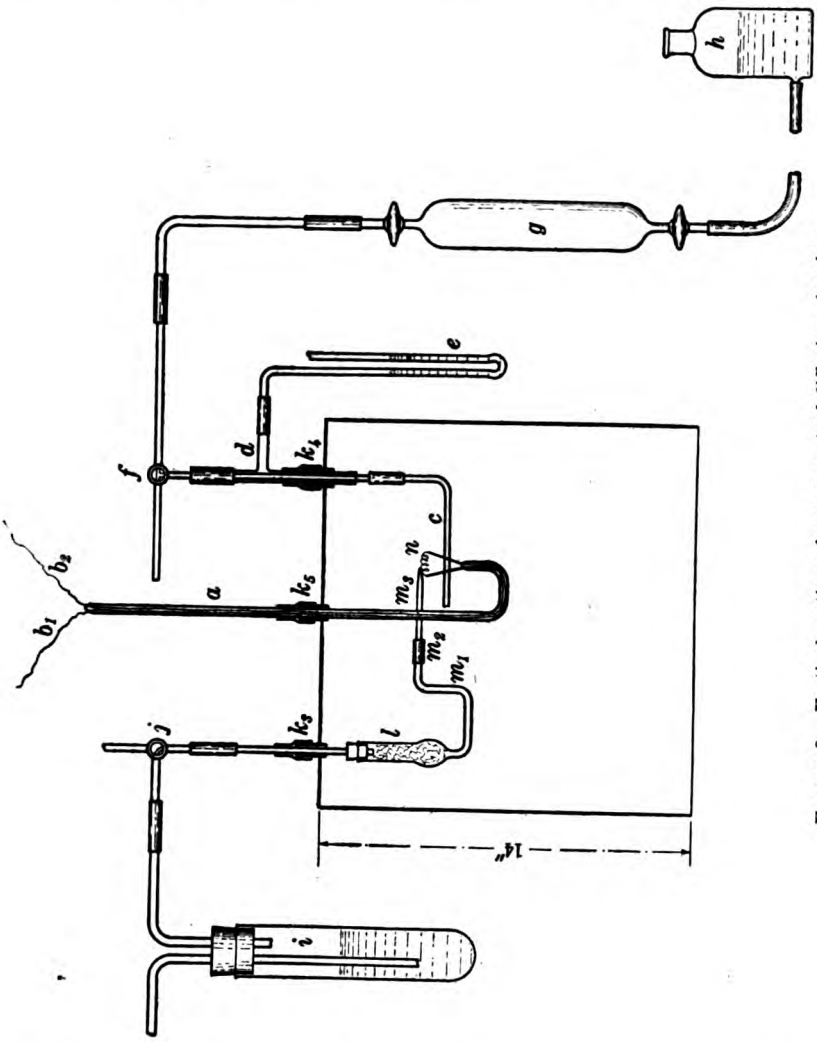

FIGURE 3.—Vertical section of upper part of diffusion chamber.

Although it is best that there should be no fines in stored coal, yet when coal of mixed sizes is to be stored, it is advantageous to handle it so that the large and the small pieces are kept evenly mixed.

In building a coal pile the aim should be to prevent fine and coarse coal segregating through the larger pieces rolling down the sides of the piles.

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COAL USED IN EXPERIMENTS.

In each experiment described in this report the coal used was from the Pittsburgh bed. Coal that had been exposed to the air several months and had oxidized to some extent was selected so as to reduce the amount of oxidation during the experiments.

The records of the experiments are given in Tables 1 to 11. For some of the experiments, 1A, 1B, 2A, 2B, 2C, 3A, 3B, 4A, 4B, 7A, 7B, as designated in these tables, the coal was crushed and carefully screened to size, and the percentage of voids was determined in a thoroughly compacted sample. In preparing the apparatus for ex-

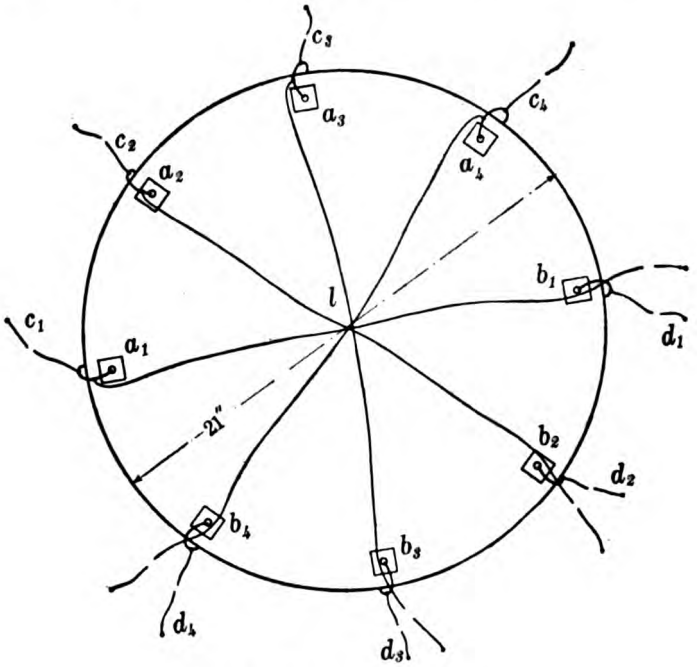

FIGURE 4.—Plan of rubber diaphragm.

periment, the coal was put in and well shaken so as to make it as compact as possible. Especial care was taken to have a minimum and uniform amount of voids and also to have the same proportion of voids in the apparatus and in the sample in which voids were determined by comparing the real volume of the coal as calculated from weight with the volume of the coal compartment. The coal was then made level with the top edge of the coal compartment.

For experiments 5A, 5B, 6A, 6B, the quantity of 2-mesh to 4-mesh coal required to fill the coal compartment was taken. To this was added the calculated volume of 40-mesh to 60-mesh coal required to

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fill the voids in the larger coal. The two sizes were evenly mixed and put into the apparatus. The percentage of voids was calculated from the data obtained in previous determinations of the voids in each size of coal.

To vary the depth of the coal compartment for experiments 6A, 6B, 7A, 7B, a sheet-metal collar of larger diameter and proper height was placed upon the fixed support *c*, figure 1, and the screen was placed on this collar. A weight of coal equal to the difference between that used to fill the deep coal compartment and to fill the shallower coal compartment, was placed on the bottom of the lower compartment. In this way the lower compartment was raised to a height equaling that to which the screen supporting the coal was raised. The gas-sampling tube *b*, figure 1, was extended so as to reach the center of the new position of the lower compartment.

For experiments 8A, 8B, 9A, 9B, 10A, 10B, the coal was derived from large storage piles of an industrial plant near Pittsburgh. That used in experiments 8A and 8B was a representative sample taken from a point midway up the side of a pile. It consisted of a mixture of all sizes from ½-inch lumps down to fine particles. The coal in the apparatus was thoroughly shaken, as in the previous experiments, to make the coal as compact as possible. This shaking caused segregation, part of the finer material going to the bottom and part of the coarser going to the top.

Experiments 10A and 10B were made with the same coal as used in 8A and 8B, but the coal was put into the apparatus without shaking and especial care was taken to have an even mixture of sizes and to prevent segregation.

A representative sample of the coal from the bottom of the storage piles was used in experiments 9 A and 9 B. It consisted mostly of lumps of from 1-inch to as large as 3-inch size that had rolled down the side of the pile. The coal was put into the apparatus as compactly as possible.

PROCEDURE IN EXPERIMENTS.

REMOVAL, BY COMBUSTION, OF OXYGEN IN UPPER COMPARTMENT.

The capacity of the upper compartment, calculated from dimensions, was 37.3 liters. This included the volume of the annular space above the water and below the level of the coal when the water in the reservoir was 3½ inches deep. To combine with the oxygen in the quantity of air required to furnish 37.3 liters of nitrogen (plus inert gas), 19.8 liters of hydrogen was required. For each experiment 19.8 liters of hydrogen measured under atmospheric conditions was used.

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Before making a combustion test the apparatus was assembled, all openings to the outside were closed, pieces of ice were put on the top to absorb the heat, and the platinum glower was heated to redness. Then the hydrogen was admitted.

The duration of each experiment was measured in hours, the time of igniting the hydrogen being taken as zero.

During the early part of the combustion the pressure rose because of the heat, but in a few minutes fell below that of the external air. The rubber stopper closing the tube a_1, figure 1, was then removed and air was allowed to flow from the outside into the lower compartment, whence it passed through the coal, raised a submerged edge of the diaphragm above the water and entered the upper compartment. When about 14 liters of hydrogen had been used, combustion became less active and the hydrogen was not consumed as fast as it entered. The pressure rose to atmospheric and at this point the rubber stopper was again replaced at a_1. The flow of hydrogen was continued till 15 to 20 minutes from the start of combustion when the required 19.8 liters had entered the diffusion apparatus. The pressure had risen and the heated glower slowly continued the combustion. After a total period of combustion of about 1¼ hours the pressure had decreased to about one-fourth inch of water. Combustion was then stopped.

To allow the temperature of the apparatus to approach that of the room the ice was removed from the top and the top wiped dry. It was allowed to stand in this condition for about five minutes.

TAKING GAS SAMPLES.

After the temperature of the parts of the apparatus had become more nearly uniform, samples of gas were taken in the manner described below. In this sampling, and in the taking of all other samples, the samples were drawn as nearly simultaneously as possible from the top and the bottom compartments so as to reduce the pressure equally in both. The two leveling bottles were placed at the same distance below the height of the column of liquid to which each was connected in order to give the same amount of suction in each sample tube. First, about 5 c. c. of gas was withdrawn and expelled into the air in order to bring fresh gas into those parts of the connecting tubes that were not filled with the glycerin solution. Then from each compartment about 50 c. c. was drawn for samples.

DIFFUSION OF OXYGEN.

Immediately after the taking of the first pair of samples diffusion was started by quickly removing the diaphragm from the surface of the coal. The time of removal of the diaphragm was recorded and considered as the starting time of the diffusion.

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The sample tubes containing the gas were disconnected and the percentage content of oxygen determined with a Haldane apparatus. In this and subsequent determinations the small amount of carbon dioxide in the gas was removed before determination of the oxygen and the percentage of oxygen calculated on the basis of a gas free from carbon dioxide.

At regular intervals samples of gas were taken, in the manner described, and analyzed. The time of taking the sample was recorded to the nearest minute.

During the experiment there was not only a diffusion of oxygen from the lower to the upper compartment, but also a diffusion of nitrogen from the upper compartment to the lower. The results obtained by analysis measure the combined effects of these two processes. For the purpose in view, however, only the diffusion of the oxygen need be considered.

While diffusion was taking place the composition of the gas in either the lower or upper compartment could not have been uniform, but must have differed at different heights in the compartment. By drawing the samples from the center of the compartments it was presumed that gas of average composition was obtained.

RESULTS OF EXPERIMENTS.

The data obtained from the different experiments are tabulated in Tables 1 to 10. In figures 5 to 25 the relations between time and the percentage of oxygen in both upper and lower compartments are shown by the circles. The upper circles show the percentage of oxygen in the lower and the lower circles that in the upper compartment. The crosses show the relation between the concentration of oxygen and the time, as calculated by the method described later.

The fifth column in Tables 1 to 10 gives the sum of the percentages of oxygen in the top and the bottom compartment. In every instance the first figure in this column is several units lower than those following, probably because the diaphragm, before its removal, separated gas mixtures of widely different composition. After removal of the diaphragm the oxygen from the coal diffused rapidly into the upper compartment, until the graduation in composition of the gas in the coal compartment was uniform from top to bottom. In this way the percentage of oxygen in the upper compartment increased without the lower compartment showing a corresponding loss, so that the sums of the analyses after the first were higher.

Another factor that may have increased this difference was hydrogen left unburned in the upper compartment. An experiment showed 1 per cent of oxygen and 1.56 per cent of hydrogen left in the upper compartment after a combustion. According to Graham's

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law [a] hydrogen should diffuse four times as fast as oxygen. A rapid diffusion of the unburned hydrogen from the upper compartment would tend to increase the percentage of oxygen in the residual gas and would not produce a corresponding decrease in the greater volume of gas below. An increase in the sum of the percentages would result. However, the diffusion of the hydrogen is comparatively rapid and its quantity is small, so that its effect may be considered negligible after the second analysis.

The percentages of oxygen in both the top and the bottom compartments were also modified by the absorption of oxygen by the coal. After experiment 3B had been made the apparatus was allowed to stand closed from the outside air and the oxygen determined after a lapse of three days. The results showed a decrease in the sum of oxygen in top and bottom amounting to 0.02 per cent per hour.

When performing the experiments with coal of larger sizes especial care was taken to have the apparatus of uniform temperature before starting the diffusion and to shield it from drafts and otherwise prevent changes of temperature during the experiment. Even with these precautions convection effects were evident and the results from the larger coals did not check well. With coals of a size of two to four mesh or smaller, no such trouble was experienced.

CALCULATION OF DIFFUSION.

Fick [b] stated his law of diffusion thus:

> The amount of salt that diffuses through a given cross-section is proportional to the difference in concentration of two cross sections lying infinitely near to one another, or is proportional to the difference in concentration.

With these principles as a basis, an equation for the diffusion was developed as described under "Theory of diffusion," on later pages. This equation, which expresses the relations between time and concentration of oxygen in the upper compartment of the apparatus during diffusion, is $t = C + K \log_{10} \frac{b-a}{c-a} (c-y)$ in which t is time C is a constant of integration, K is a constant for each experiment and is numerically equal to the time required for the difference in concentration of oxygen in the lower and upper compartments to change from a difference of 10 per cent to a difference of 1 per cent; a is concentration of oxygen in the upper compartment at beginning of diffusion; b is concentration of oxygen in the lower compartment at beginning of diffusion; c is concentration of oxygen throughout the whole apparatus when concentration becomes uniform; and y is the variable concentration of oxygen in the upper compartment at any time, t.

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[a] Graham, T., On the law of the diffusion of gases: Philos. Mag., ser. 3, vol. 2, 1833, p. 175.

[b] Fick, A., Über Diffusion: Ann. Phys. Chemie, Bd. 94, 1855, pp. 59–86.

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By substituting values for t, y, a, b, c, obtained by experiment, in the equation, values for C and K may be calculated for each experiment.

With the calculated values for C and K substituted in the equations, values for t for the assumed values of y, 0, 1, 2, 3, . . ., have been calculated and are given in Tables 1 to 10 in the succeeding chapter on Theory of Diffusion. On figures 6 to 15 these calculated values are represented by the $\times$ marks. The reader should note the very close agreement between the curves representing the experimental and the calculated data. This agreement indicates that the diffusion of oxygen through the atmosphere in the voids of broken coal closely follows the laws stated by Fick.

As expressed above, the values of K are numerically equal to the time required for the difference in concentration of the oxygen in the lower and the upper compartment to change from a difference of 10 per cent to a difference of 1 per cent. By comparing the values obtained for K from the results of the various experiments, the relations between the rates of diffusion of oxygen under the different experimental conditions may be found.

EFFECT OF THE SIZE OF COAL ON DIFFUSION.

Table 11 shows the values for constant K, which express decimal hours. In experiments 1A, 1B, 2A, 2B, 2C, 3A, 3B, 4A, 4B, four different sizes of coal were used, but the depth was the same. Although the sizes of coal used varied through wide limits, the percentages of voids in the coals fall between comparatively narrow limits and for this comparison may be considered equal. By the well-known example, a measure of bird shot weighs the same as a measure of buckshot. Hence the analogy between the proportion of void space in a mass of uniformly sized shot or spheres, which is independent of the actual size of the spheres, and the void space in uniformly sized coal is evident, and the percentage of solid and of voids should be the same in each unit volume of uniformly sized coal, regardless of the relative sizes of coal in the different lots compared. In these experiments with four widely different sizes of coal, the two variables, depth and percentage of voids, are comparatively constant, and K is quite constant. The greatest deviation of K is for the largest coal, 1-inch to 2-inch lumps, and here convection is largely responsible for the smaller values of K.

It may be concluded, then, that when the size of particles in a coal mass is uniform, the size itself, within the limits of the experiments, has no effect on the rate of diffusion of oxygen through the coal.

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EFFECT OF THE PROPORTION OF VOIDS ON DIFFUSION.

In figure 26 the relations between the percentage of voids and K are shown for experiments with coals 8 inches in depth. If the percentage of voids were zero—that is, if the coal mass were solid—no diffusion could take place through it, and K, which measures time of diffusion, would become infinity. At the other extreme there might be 100 per cent of voids, or no coal whatever in the coal compartment. Then the time of diffusion, or K, would be greater than zero but smaller than any value obtained where coal obstructs diffusion. If a smooth curve is drawn through these two assumed extreme points and the average intermediate points found by experiment, as in figure 26, the curve is seen to approximate a rectangular hyperbola (the dotted line) symmetrical with respect to the coordinate axes.

An attempt was made to show that the experimental curve is a hyperbola that probably deviates slightly from the symmetrically placed hyperbola because of certain features peculiar to the conduct of the experiments. However, the experiments only warrant the making of these deductions:

In coal aggregates having different proportions of voids, but with other conditions the same, reduction in the percentage of voids increases the time required for a definite amount of diffusion by an amount somewhat less than is proportionate to the decrease in voids.

The product of the percentage of voids and the time for a given amount of diffusion of oxygen increases regularly with increase in percentage of voids.

This relation may be better understood if stated in terms of figures, thus: If a certain amount of voids allows a definite amount of diffusion to occur in a certain time, and the amount of voids is then reduced to one-half its former value but other conditions are kept constant, the time required for the same amount of diffusion will be somewhat less than twice the time required under the first condition.

EFFECT OF DEPTH OF COAL ON DIFFUSION.

Enough data have not been obtained for definite conclusions regarding the effect of depth of coal. However, it might be expected that the increase in time required for a given diffusion would be proportional to the increase in depth of coal. In Table 11 data from experiments 6A and 6B are the results obtained with a coal $3\frac{3}{4}$ inches deep. Using these data and calculating the time required for diffusion through 8 inches depth of coal by direct proportion, there is obtained:

$3\frac{3}{4} : 3.92 :: 8 : K. \quad K=8.36.$
$3\frac{3}{4} : 3.95 :: 8 : K. \quad K=8.42.$

In two experiments with the same coal 8 inches in depth, experiments 5A and 5B, K was found to be 8.54 and 8.77.

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In experiments 7A and 7B data were obtained from coal 5¾ inches in depth. From these results the time required for a same amount of diffusion through a layer of coal 8 inches deep, by direct proportion, is:

$$5\tfrac{3}{4} : 3.03 :: 8 : K. \quad K=4.22.$$
$$5\tfrac{3}{4} : 3.04 :: 8 : K. \quad K=4.23.$$

The same coal used in a layer 8 inches deep in experiments 2A, 2B, and 2C gave the values 4.11, 4.14, and 4.18 for K.

The agreement between the lengths of time required for a given amount of diffusion, calculated on the assumption that the diffusion through coal varies inversely with the depth, and those found by experiment on the same depth, is reasonably close. The indications, then, point to the correctness of the assumption.

PRACTICAL APPLICATIONS OF RESULTS.

Under some circumstances air supplied by convection may act as the main source of deterioration and spontaneous combustion in stored coal, but this paper considers only diffusion and its effects. The results of the experiments described show especially the importance of the proportion of voids in a mass of stored coal exposed to the air, in determining the possible amount of oxidation through oxygen entering the mass by diffusion. The amount of voids in any mixture of coal pieces can be kept low by having the large and small size coal uniformly mixed. If the proportion of small size to large were such that the volume of the small were just enough to fill the voids in the larger size, and this process repeated indefinitely with still smaller sizes, a limit of no voids would be approached. In practice such an arrangement could not be made. But, on the other hand, it is an ideal to be approached as nearly as practicable.

Separation of fine and of coarse coal is incident to most methods of handling coal. This separation serves to increase the amount of voids in the segregated parts of the mass. Segregation takes place very readily when a pile is made, as is usually the case, by adding each increment at the apex of the pile. Most of the largest lumps then roll to the bottom, and there is a somewhat regular gradation of sizes up the side of the pile, with the smallest sizes at the top.

As the result of investigations of spontaneous fires in coal on shipboard, the New South Wales Commission[a] found that in every instance investigated the spontaneous fire originated in the heap of dust under the hatchway. Dust particles expose a larger surface per unit of weight to the action of oxygen. But, such considerations aside, this investigation of diffusion explains how segregated dust in

[a] Threlfall, Richard. The spontaneous heating of coal, particularly during shipment: Jour. Soc. Chem. Ind., vol. 28, 1909, pp. 759–773.

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a mass of coal receives more oxygen from the outside air by diffusion than it would receive if the same mass of coal had been stored so as to have a lower proportion of voids.

Segregation in coal piles may be largely prevented by carefully building the pile so as to prevent coal rolling down the sides. The ground on which the pile is to stand may first be covered evenly and completely with a layer of coal. On this first layer a second layer may be placed with equal care, then a third, and so on.

It has been shown that a mass of very small, uniform coal particles has no practical effect in retarding the diffusion of oxygen through it. And the proportion of voids in very fine coal, when uniformly sized, is the same as in lump coal when uniformly sized. However, it might have been expected that the smaller size would retard diffusion because of increased friction between coal and gas molecules, each of which has its own velocity, owing to the greatly increased surface of contact. That very fine coal oxidizes more readily than coarse and is more liable to spontaneous combustion is well understood. In addition to the greater danger from other sources, under otherwise similar conditions, the experiments described show that by diffusion oxygen is brought from the air to the interior of a mass of fine coal just as readily as to the interior of a similar mass of larger sized coal.

CONCLUSIONS.

The results of the investigations described in this report may be summed up in these conclusions:

1. The principles stated in Fick's law of diffusion have been found applicable to the diffusion of oxygen through the atmosphere in the voids of broken coal.

2. In a mass of broken coal, through which oxygen is diffusing, the size of the pieces has within practicable limits no effect on the rate of diffusion, all other conditions being constant.

3. If the proportion of voids in a mass of coal pieces is varied, the time required for a definite diffusion of oxygen increases approximately in inverse proportion to the percentage of voids. The product of the percentage of voids and the time required for a given diffusion increases directly with the increase in the percentage of voids.

4. The amount of oxygen diffusing through the interstices in a mass of coal pieces seems to vary inversely as the depth of the coal. Enough experiments to justify a more definite conclusion have not been made.

5. Coal stored in lumps or smaller pieces of uniform size contains a high proportion of voids and oxygen diffuses readily through the mass. In run-of-mine or slack coal, which contain a great variety of sizes, the proportion of voids is less and the diffusion of oxygen is slower.

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6. Mixing different sized pieces in a mass tends to reduce the proportion of voids. In storing coal in the air factors other than diffusion may be accelerated or retarded by changes in voids; but if diffusion alone be considered, mixing the sizes of coal will reduce the oxygen entering the pile by diffusion.

7. Building of a coal pile, so as to reduce or prevent segregation of the large and the small pieces, will lessen the proportion of voids in the pile, will tend to keep down the amount of oxygen entering the pile by diffusion, and thus reduce oxidation from this source.

THEORY OF DIFFUSION.

If, during the diffusion of the oxygen through the coal, the gradation of the percentage of oxygen with the height of the coal is regular, it may be assumed on the basis of Fick's law that the concentration of oxygen in the upper compartment increases at a rate directly proportional to the difference between the concentration of the oxygen in the lower and in the upper compartment of the diffusion apparatus.

In order to express these relations in algebraic form for use with the data obtained from the experiments, all concentrations of gas being expressed in percentage by volume, let

a=the concentration of oxygen in the upper compartment at the start of diffusion;

b=the concentration of oxygen in the lower compartment and in the coal compartment at the start of diffusion;

c=the concentration of oxygen throughout the apparatus when the concentration becomes uniform;

v=the volume of gas above the diaphragm;

V=the volume of gas below the diaphragm.

Let

t be any time after starting the experiment and y be the concentration of oxygen in the upper compartment at any time, t.

Then at any time during diffusion the volume of oxygen that has entered the upper compartment is

(1) $$\frac{v\ (y-a)}{100}$$

The lower compartment has lost a volume of oxygen equal to that gained by the upper (neglecting the changes of amounts of oxygen in the coal compartment, which are small in comparison). So the percentage of oxygen lost by the lower compartment at any time, t, is:

(2) $$\frac{v}{V}(y-a).$$

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Both members of the following equation express the total volume of oxygen in the apparatus:

(3) $$av+bV=c(v+V).$$

Hence:

(4) $$\frac{v}{V}=\frac{b-c}{c-a}.$$

Substituting the above value of $\frac{v}{V}$ in expression 2, it becomes:

(5) $$\frac{b-c}{c-a}(y-a).$$

Subtracting this from the percentage of oxygen in the lower compartment at the beginning of diffusion gives the concentration of oxygen in the lower compartment at any time:

(6) $$b-\frac{b-c}{c-a}(y-a).$$

Then the difference in percentage of oxygen in the lower and upper compartments at any time is expressed by (6) minus y, which by transformation becomes:

(7) $$\frac{b-}{c-a}(c-y).$$

Now, if the rate of increase in percentage of oxygen in the upper compartment is directly proportional to the difference in concentration of oxygen in the lower and upper compartments at any time, the following equation expresses these relations:

(8) $$\frac{dy}{dt}=k\frac{b-a}{c-a}(c-y).$$

By integration this gives:

(9) $$t=\mathrm{C}-\frac{c-a}{b-a}\times\frac{\log_e 10}{k}\mathrm{Log}_{10}\frac{b-a}{c-a}(c-y).$$

Let

(10) $$-\frac{c-a}{b-a}\times\frac{\log_e 10}{k}=\mathrm{K}.$$

Then (9) becomes:

(11) $$t=\mathrm{C}+\mathrm{K}\log_{10}\frac{b-a}{c-a}(c-y).$$

Equation 11 gives the relations between time and percentage of oxygen in the upper compartment that were being sought.

In equation 11 the quantity $\frac{b-a}{c-a}(c-y)$ equals the difference in concentration of oxygen, expressed in per cent, in the lower and upper compartment at any time. When this difference becomes equal to unity the logarithm of the quantity is zero and equation 11 becomes:

(12) $$t'=\mathrm{C}.$$

C, then, is numerically equal to the time that is required for the difference in percentages of oxygen in the upper and lower compart-

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ments to attain a value of 1, the time being measured from the point arbitrarily assumed to be 0.

When the difference in concentration of oxygen in the upper and lower compartments becomes equal to 10 per cent, the log of the difference is unity. Equation 11 then becomes:

(13) $$t''=C+K.$$

Subtracting equation 12 from 13 gives the relation between time and the constant K:

(14) $$t''-t'=K.$$

The constant K, then, is numerically equal to the time that is required for the difference in concentration of oxygen in the lower and upper compartments to change from a value of 10 per cent to a value of 1 per cent.

By comparing the values obtained for K from the results of the various experiments, the relations between the rates of diffusion of oxygen under the different experimental conditions may be found.

METHOD OF EVALUATING C AND K.

To illustrate the process that was used in calculating the values for C and K from the experimental data, the data from experiment 1A given in Table 1 will be used.

Referring to the general equation (11): $t=C+K\log_{10}\frac{b-a}{c-a}(c-y)$, the values a and b are obtained directly from the data of Table 1, experiment 1A.

The value of c is obtained by averaging the sums in the fifth column, omitting the first figure, and dividing by 2.

(15) $$c=12.43.$$

Substituting these values in equation 11, this equation is obtained:

(16) $$t=C+K\log_{10}(20.88-1.680y).$$

By substituting corresponding values found for t and y, as many different equations can be formed from (16) as there are analyses. Then by taking any two of these equations, values for C and K can be calculated. In all the calculations that were made, the figures from either the fourth or the fifth analyses were taken together with each of the others in turn, and C and K evaluated. In making the calculations from experiment 1A, the fourth analysis was used to pair with each of the others.

Exception may be taken to the use of one set of values for t and y in making the pairs of equations, as the chosen figures affect very unequally the values for C and K. Inaccuracies in the chosen figures due to analytical error and other causes are thus given greater weight. On the other hand, the results found in the fourth or fifth analyses

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are less affected by interfering actions taking place in the apparatus. The earlier data are more affected by diffusion of the hydrogen. That obtained later is more affected by absorption of oxygen by the coal. Considering these interferences, the data obtained from the fourth or fifth analyses may be considered to most nearly approach that which might be obtained under ideal conditions. For these reasons one or the other was chosen and used in each calculation for values of C and K. Which analytical result was used in this way is mentioned below the tables of data for each experiment.

Thus in experiment 1A, substituting the figures from the first and fourth analyses in equation 16 and solving, C=5.53 and K=−3.358.

Analyses second and fourth give C=6.06, K=−4.086.

Analyses third and fourth give C=6.20, K=−4.279.

Analyses fifth and fourth give C=6.25, K=−4.343.

Analyses sixth and fourth give C=5.97, K=−3.960.

Analyses seventh and fourth give C=5.92, K=−3.888.

Analyses eighth and fourth give C=5.80, K=−3.735.

The values for C and K found by use of the results of the first analysis were always materially less than those found with the other analyses. This was because of the rapid diffusion of the oxygen from the coal compartment into the upper compartment immediately after removing the diaphragm, and to a less extent because of the rapid diffusion of the hydrogen.

The results obtained from the other analyses taken in turn show fair agreement, though the divergence here is larger than usual. Omitting C and K, obtained by use of the first analysis, and averaging the rest gives:

(17) $$C=6.03.$$

(18) $$K=-4.05.$$

By substituting these values for C and K equation 11 becomes:

(19) $$t=6.03-4.05 \log_{10} (20.88-16.80y).$$

Giving y in equation 19 values 0, 1, 2, 3, ... , n, shown in the sixth column under experiment 1A, Table 1, and solving, the corresponding values for t, given in the first column, are obtained. The results calculated in this way for the various experiments are shown in figures 5 to 25 by the × marks.

The agreement between the curves of the experimental data and the data calculated on the assumption that at any time the rate of diffusion of oxygen is directly proportional to the difference in concentration of oxygen in the lower and upper compartments is vary marked. The principles of diffusion stated by Fick are found, then, to apply closely in the case of the diffusion of oxygen through the atmosphere in the voids of broken coal.

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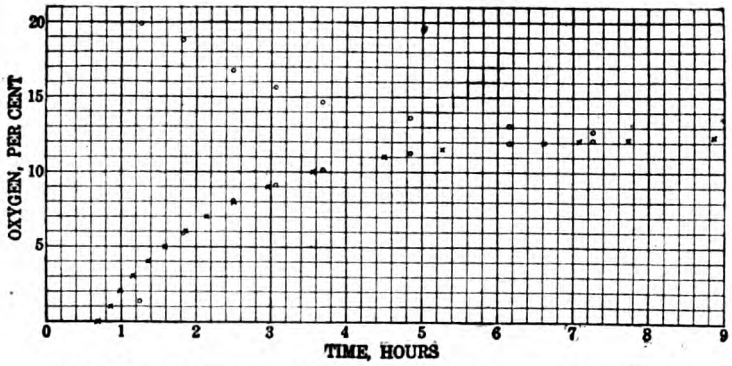

FIGURE 5.—Graph from data of experiment 1A given in Table 1.

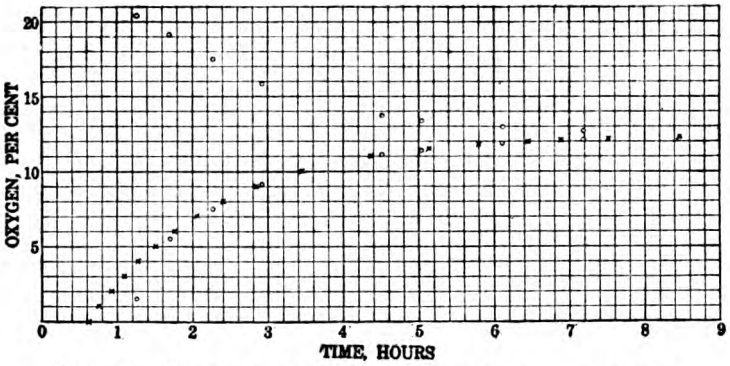

FIGURE 6.—Graph from data of experiment 1B given in Table 1.

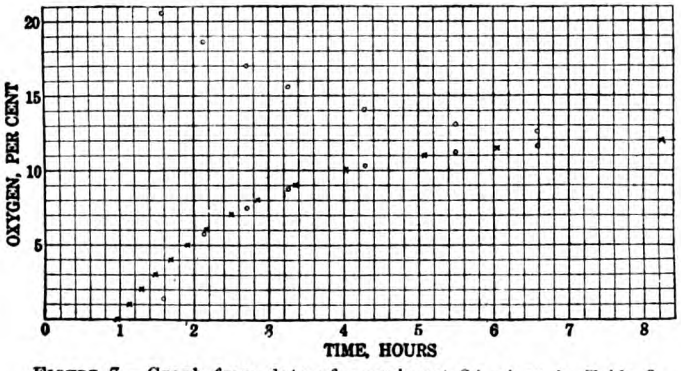

FIGURE 7.—Graph from data of experiment 2A given in Table 2.

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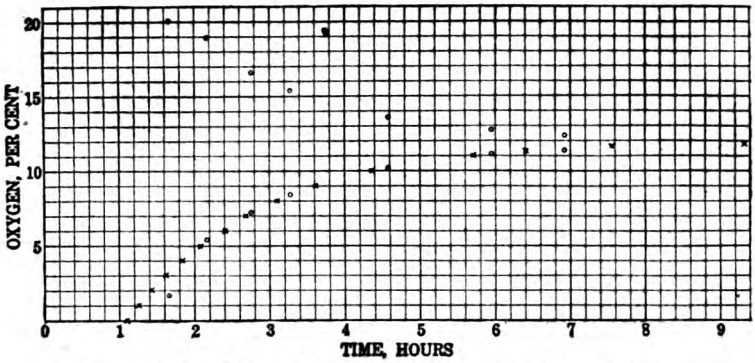

FIGURE 8.—Graph from data of experiment 2B given in Table 2.

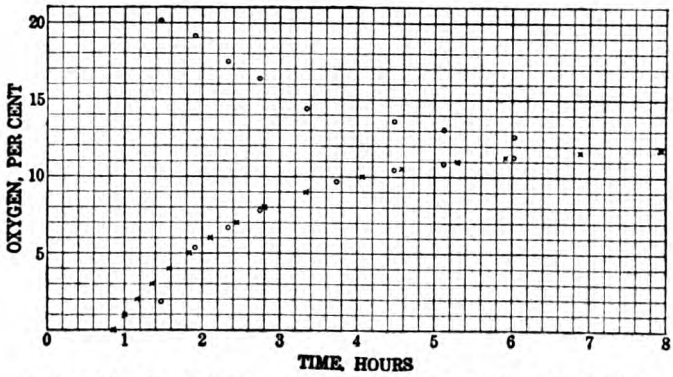

FIGURE 9.—Graph from data of experiment 2C given in Table 2.

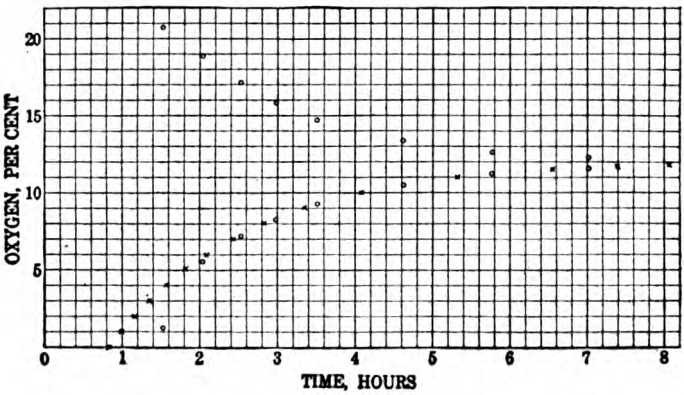

FIGURE 10.—Graph from data of experiment 3A given in Table 3.

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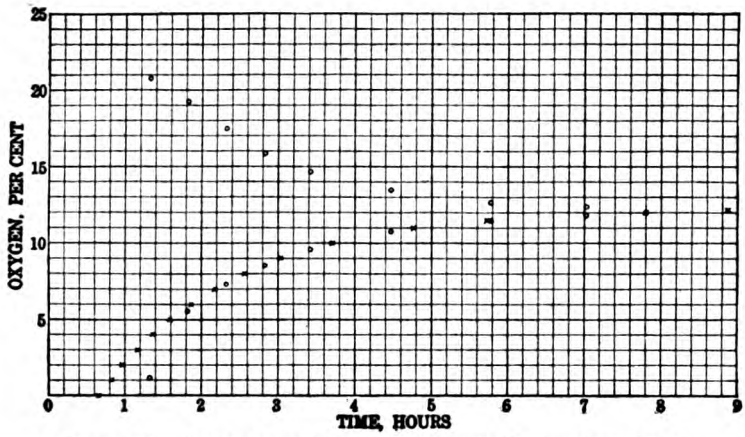

FIGURE 11.—Graph from data of experiment 3B given in Table 3.

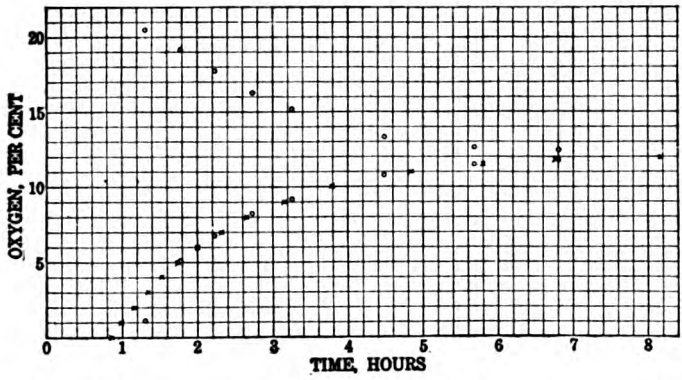

FIGURE 12.—Graph from data of experiment 4A given in Table 4.

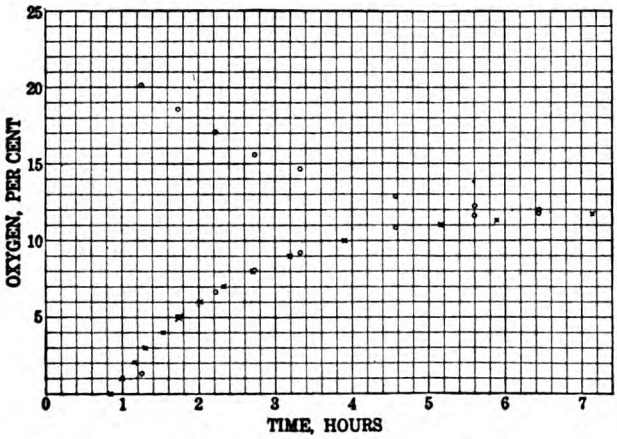

FIGURE 13.—Graph from data of experiment 4B given in Table 4.

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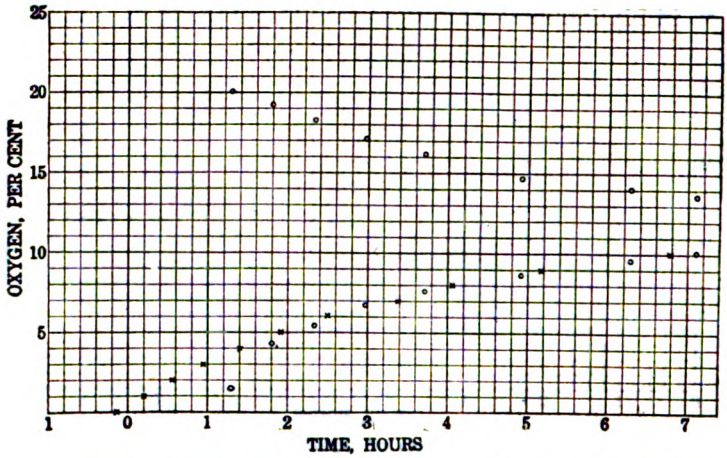

FIGURE 14.—Graph from data of experiment 5A given in Table 5.

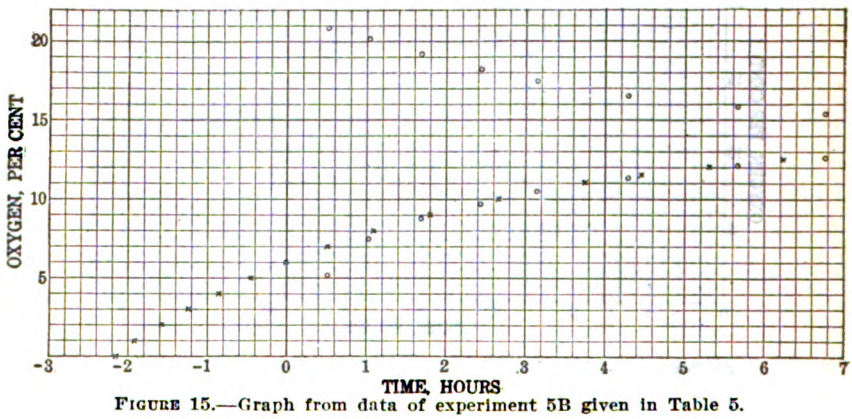

FIGURE 15.—Graph from data of experiment 5B given in Table 5.

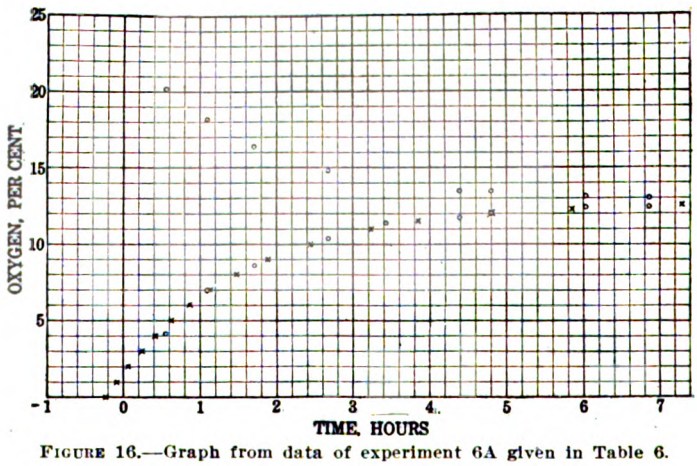

FIGURE 16.—Graph from data of experiment 6A given in Table 6.

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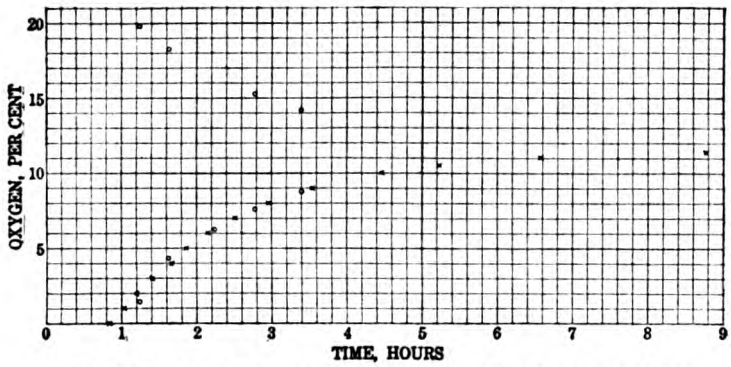

FIGURE 17.—Graph from data of experiment 6B given in Table 6.

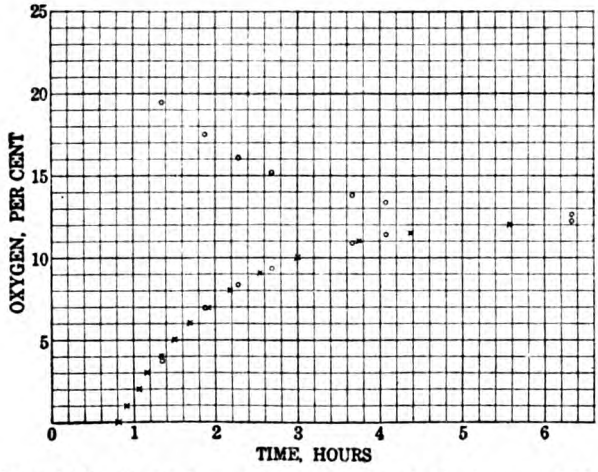

FIGURE 18.—Graph from data of experiment 7A given in Table 7.

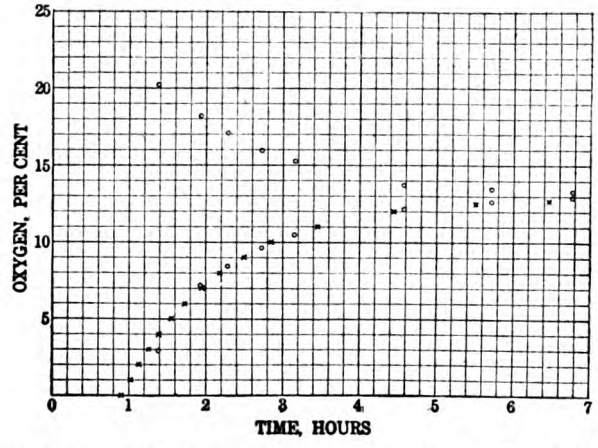

FIGURE 19.—Graph from data of experiment 7B given in Table 7.

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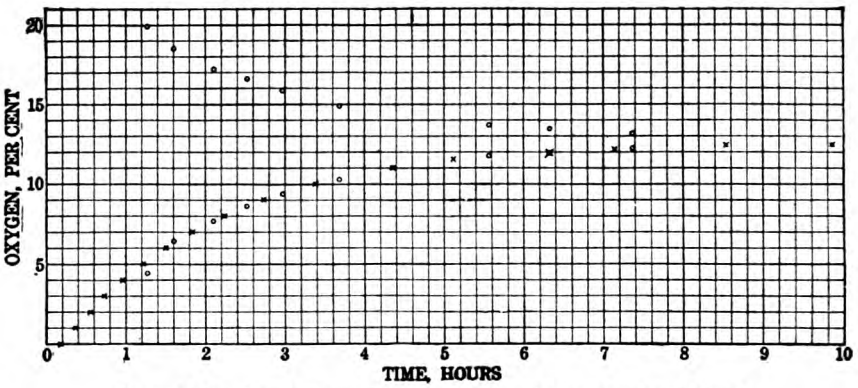

FIGURE 20.—Graph from data of experiment 8A given in Table 8.

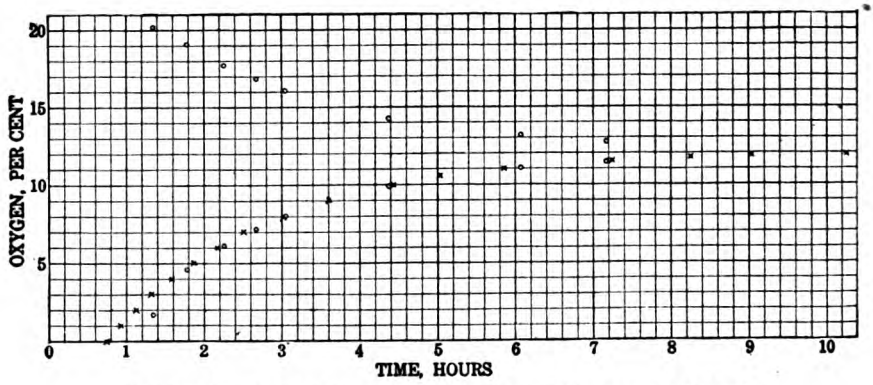

FIGURE 21.—Graph from data of experiment 8B given in Table 8.

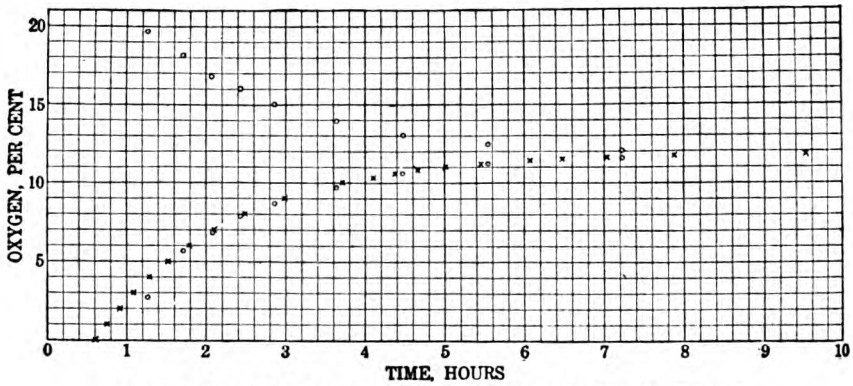

FIGURE 22.—Graph from data of experiment 9A given in Table 9.

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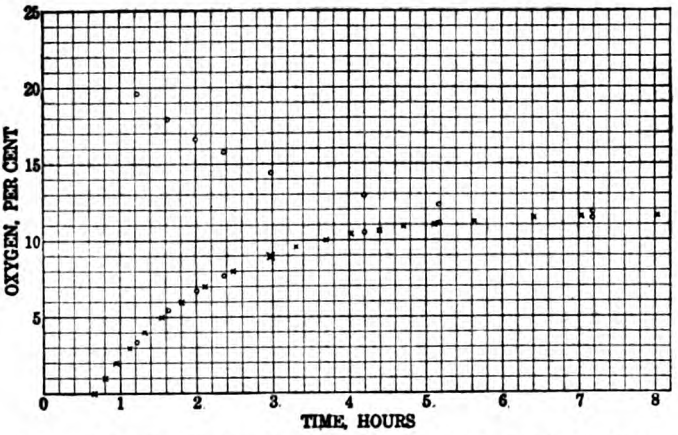

FIGURE 23.—Graph from data of experiment 9B given in Table 9.

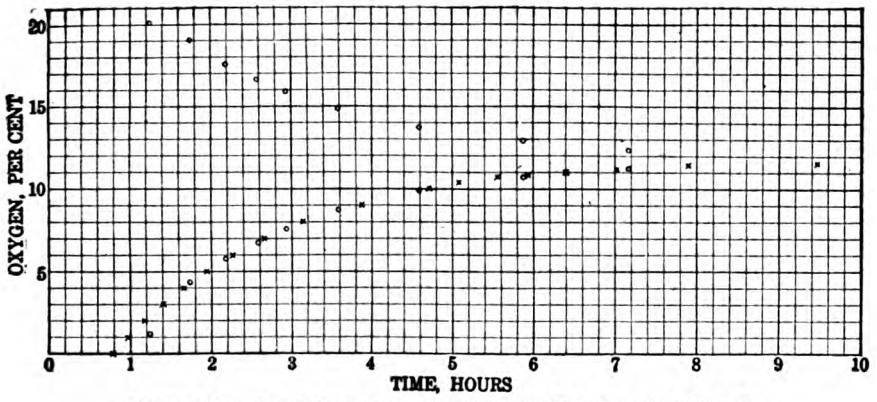

FIGURE 24.—Graph from data of experiment 10A given in Table 10.

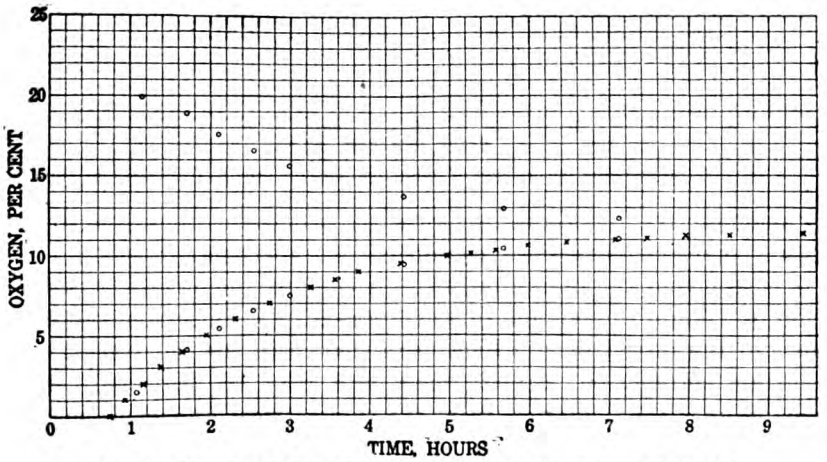

FIGURE 25.—Graph from data of experiment 10B given in Table 10.

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EFFECT OF PROPORTION OF VOIDS.

In figure 26 the relations between the percentages of voids and the time required for a definite amount of diffusion to occur are plotted. The dotted curve is a hyperbola placed symmetrically with respect to the axes. The curve drawn in full is a hyperbola unsymmetrically placed. In figure 27 the percentages of voids are plotted as abscissas and the products of the percentages of voids and K as ordinates. Here the dotted line parallel to the axes of abscissas corresponds to

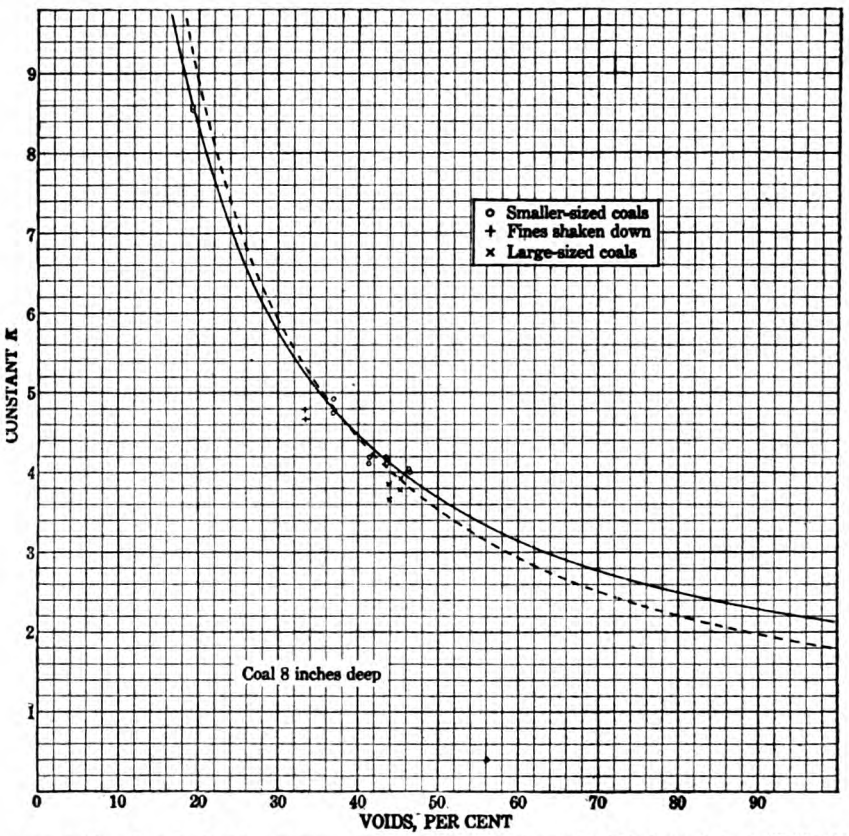

FIGURE 26.—Graph showing percentage of voids against constant K, from data in Table 11.

the symmetrical hyperbola in figure 26, and the oblique line drawn in full corresponds to the unsymmetrical hyperbola.

It is seen that the points fall nearest the unsymmetrical hyperbola of figure 26 and the oblique line of figure 27. Points from the large coal and the mixed fines, which were shaken in the apparatus, with resulting segregation, deviate most and may be neglected. It is probable that the deviation from the symmetrical hyperbola may be due to certain features inherent in the experiments as performed

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and that under ideal experimental conditions the symmetrical hyperbola would represent the relations.

Under the ideal conditions the atmosphere in the lower and the upper compartments would be uniform in concentration throughout each compartment. Under the conditions used the concentration of oxygen near the surface of the coal in the upper compartment was undoubtedly greater than at a point farther away, and vice versa for the lower compartment. The excess of oxygen at the one surface

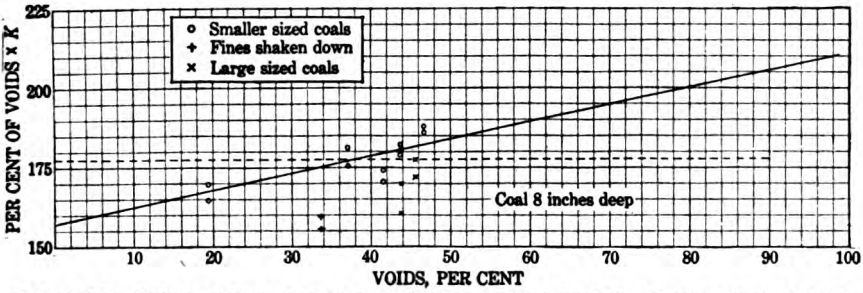

FIGURE 27.—Graph showing percentage of voids against product of percentage of voids and constant K, from data in Table 11.

and the deficiency at the other would tend to cause a lag in the rate of diffusion when compared with that under the ideal conditions, and the lag would be greater with greater percentage of voids and greater diffusion. An explanation of the cause of the unsymmetrical hyperbola may be found in this lag.

Although these considerations are worthy of note, the conclusions have been drawn from the relations of the unsymmetrical hyperbola as most nearly representing the results found.

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TABULATED DATA.

TABLE 1.—*Data from 40 to 60 mesh coal, 8 inches thick; proportion of voids, 46.5 per cent.*

EXPERIMENT 1A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.69					0.00
0.86					1.00
0.99					2.00
1.17					3.00
1.27	1	19.93	1.41	21.34	
1.37					4.00
1.59					5.00
1.82	2	18.79	5.93	24.72	
1.85					6.00
2.14					7.00
2.48	3	16.78	8.01	24.79	
2.50					8.00
2.95					9.00
3.05	4	15.70	9.18	24.88	
3.56					10.00
3.68	5	14.72	10.10	24.82	
4.49					11.00
4.83	6	13.67	11.27	24.94	
5.25					11.50
6.15	7	13.07	11.91	24.98	
6.61					12.00
7.08					12.10
7.25	8	12.75	12.18	24.93	
7.73					12.20
8.86					12.30

K was evaluated with analysis No. 4. Equation, $t=6.03-4.05 \log_{10}(20.88-1.680y)$. K=4.05.

EXPERIMENT 1B.

0.61					0.00
0.76					1.00
0.92					2.00
1.09					3.00
1.25	1	20.42	1.57	21.99	
1.28					4.00
1.51					5.00
1.70	2	19.15	5.52	24.67	
1.76					6.00
2.05					7.00
2.27	3	17.48	7.52	25.00	
2.40					8.00
2.85					9.00
2.93	4	15.84	9.15	24.99	
3.45					10.00
4.37					11.00
4.50	5	13.80	11.07	24.87	
5.03	6	13.43	11.43	24.86	
5.11					11.50
5.79					11.80
6.10	7	12.98	11.87	24.85	
6.44					12.00
6.88					12.10
7.18	8	12.75	12.12	24.87	
7.52					12.20
8.45					12.30
75.08	9	11.01	11.01	22.02	

K was evaluated with analysis No. 4. Equation, $t=5.96-4.01 \log_{10}(21.58-1.735y)$. K=4.01.

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TABLE 2.—*Data from 4 to 10 mesh coal, 8 inches thick; proportion of voids, 43.6 per cent.*

EXPERIMENT 2A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.97					0.00
1.12					1.00
1.28					2.00
1.47					3.00
1.58	1	20.60	1.43	22.03	
1.68					4.00
1.91					5.00
2.13	2	18.66	5.79	24.45	
2.17					6.00
2.49					7.00
2.70	3	16.99	7.54	24.53	
2.86					8.00
3.25	4	15.62	8.78	24.40	
3.35					9.00
4.02					10.00
4.28	5	14.06	10.31	24.37	
5.09					11.00
5.48	6	13.12	11.23	24.35	
6.05					11.50
6.58	7	12.66	11.69	24.35	
8.24					12.00

K was evaluated with analysis No. 5. Equation, $t=6.46-4.11 \log_{10}(21.72-1.779y)$. K=4.11.

EXPERIMENT 2B.

1.09					0.00
1.25					1.00
1.42					2.00
1.61					3.00
1.67	1	20.04	1.72	21.76	
1.83					4.00
2.07					5.00
2.17	2	18.96	5.46	24.42	
2.40					6.00
2.68					7.00
2.75	3	16.65	7.27	23.92	
3.09					8.00
3.27	4	15.40	8.43	23.83	
3.61					9.00
4.37					10.00
4.58	5	13.60	10.25	23.85	
5.69					11.00
5.95	6	12.70	11.13	23.83	
6.40					11.30
6.92	7	12.35	11.44	23.79	
7.55					11.60
9.32					11.80

K was evaluated with analysis No. 4. Equation, $t=6.60-4.14 \log_{10}(21.40-1.794y)$. K=4.14.

EXPERIMENT 2C.

0.84					0.00
1.00					1.00
1.17					2.00
1.36					3.00
1.47	1	20.14	1.81	21.95	
1.58					4.00
1.82					5.00
1.90	2	19.10	5.32	24.42	
2.10					6.00
2.33	3	17.49	6.74	24.23	
2.43					7.00
2.73	4	16.35	7.80	24.15	
2.80					8.00
3.34					9.00
3.73	5	14.43	9.62	24.05	
4.06					10.00
4.47	6	13.63	10.41	24.04	
4.58					10.50
5.12	7	13.10	10.89	23.99	
5.29					11.00
5.90					11.30
6.02	8	12.66	11.30	23.96	
6.87					11.60
7.95					11.80

K was evaluated with analysis No. 4. Equation, $t=6.42-4.18 \log_{10}(21.58-1.792y)$. K=4.18.

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TABLE 3.—*Data from 2 to 4 mesh coal, 8 inches thick; proportion of voids, 41.5 per cent.*

EXPERIMENT 3A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.83					0.00
0.99					1.00
1.16					2.00
1.35					3.00
1.52	1	20.72	1.25	21.97	
1.56					4.00
1.81					5.00
2.03	2	18.80	5.60	24.40	
2.08					6.00
2.42					7.00
2.53	3	17.11	7.23	24.34	
2.82					8.00
2.97	4	15.81	8.26	24.07	
3.34					9.00
3.50	5	14.69	9.26	23.95	
4.07					10.00
4.62	6	13.41	10.51	23.92	
5.31					11.00
5.77	7	12.58	11.20	23.78	
6.54					11.50
7.03	8	12.30	11.57	23.87	
7.39					11.70
8.05					11.80

K was evaluated with analysis No. 5. Equation, $t=6.43-4.19 \log_{10}(21.73-1.087y)$. K=4.19.

EXPERIMENT 3B.

0.65					0.00
0.81					1.00
0.97					2.00
1.16					3.00
1.32	1	20.80	1.18	21.98	
1.36					4.00
1.59					5.00
1.83	2	19.23	5.61	24.84	
1.86					6.00
2.18					7.00
2.32	3	17.47	7.36	24.83	
2.55					8.00
2.83	4	15.88	8.59	24.47	
3.03					9.00
3.42	5	14.71	9.62	24.33	
3.70					10.00
4.47	6	13.50	10.78	24.28	
4.77					11.00
5.71					11.50
5.78	7	12.71	11.49	24.20	
7.02	8	12.40	11.81	24.21	
7.79					12.00
8.85					12.10
11.89					12.20
76.48	9	11.51	11.48	22.99	

K was evaluated with analysis No. 5. Equation, $t=6.15-4.11 \log_{10}(21.73-1.778y)$. K=4.11.

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TABLE 4.—*Data from 1 to 2 inch coal, 8 inches thick, proportion of voids, 45.3 per cent.*

EXPERIMENT 4A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.84					0.00
0.99					1.00
1.15					2.00
1.30	1	20.52	1.12	21.64	
1.33					3.00
1.52					4.00
1.75					5.00
1.78	2	19.15	5.12	24.27	
2.00					6.00
2.22	3	17.72	6.79	24.51	
2.31					7.00
2.67					8.00
2.72	4	16.28	8.21	24.49	
3.14					9.00
3.25	5	15.19	9.22	24.41	
3.79					10.00
4.48	6	13.43	10.82	24.25	
4.84					11.00
5.67	7	12.67	11.52	24.19	
5.80					11.50
6.78					11.80
6.80	8	12.38	11.76	24.14	
8.18					12.00

K was evaluated with analysis No. 5. Equation, $t=6.07-3.93 \log_{10}(21.39-1.758y)$. K=3.93.

EXPERIMENT 4B.

0.85					0.00
1.00					1.00
1.15					2.00
1.25	1	20.19	1.30	21.49	
1.33					3.00
1.53					4.00
1.73	2	18.65	5.01	23.66	
1.75					5.00
2.01					6.00
2.22	3	17.01	6.69	23.70	
2.32					7.00
2.70					8.00
2.72	4	15.68	8.04	23.72	
3.19					9.00
3.32	5	14.58	9.22	23.80	
3.90					10.00
4.57	6	12.89	10.82	23.71	
5.17					11.00
5.60	7	12.20	11.59	23.79	
5.88					11.30
6.43	8	11.96	11.77	23.73	
7.16					11.60

K was evaluated with analysis No. 5. Equation, $t=5.88-3.79 \log_{10}(21.23-1.790y)$. K=3.79.

NOTE.—The results of the sixth, seventh, and eighth analyses were not used in making the calculations.

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TABLE 5.—*Data from mixed 2 to 4 and 40 to 60 mesh coal, 8 inches thick, calculated proportion of voids in mixture, 19.3 per cent.*

EXPERIMENT 5A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
−0.13					0.00
+ .20					1.00
.56					2.00
.96					3.00
1.28	1	20.03	1.52	21.55	
1.41					4.00
1.80	2	19.28	4.27	23.55	
1.92					5.00
2.32	3	18.23	5.46	23.69	
2.50					6.00
2.97	4	17.12	6.77	23.89	
3.19					7.00
3.70	5	16.17	7.62	23.79	
4.05					8.00
4.90	6	14.75	8.72	23.47	
5.17					9.00
6.27	7	14.02	9.64	23.66	
6.78					10.00
7.10	8	13.61	10.08	23.69	
9.68					11.00
13.24					11.50

K was evaluated with analysis No. 5. Equation, $t=11.21-8.54 \log_{10}(21.24-1.794y)$. $K=8.54$.

EXPERIMENT 5B.

−2.15					0.00
−1.92					1.00
−1.57					2.00
−1.23					3.00
− .86					4.00
− .46					5.00
− .01					6.00
+ .50	1	20.92	5.22	26.14	
.51					7.00
1.02	2	20.19	7.56	27.75	
1.09					8.00
1.68	3	19.19	8.77	27.96	
1.79					9.00
2.43	4	18.24	9.77	28.01	
2.65					10.00
3.13	5	17.49	10.47	27.96	
3.75					11.00
4.28	6	16.54	11.35	27.92	
4.45					11.50
5.30					12.00
5.65	7	15.81	12.12	27.93	
6.43					12.50
6.75	8	15.36	12.55	27.91	
8.00					13.00
10.74					13.50

K was evaluated with analysis No. 5. Equation, $t=10.13-8.77 \log_{10}(25.10-1.796y)$. $K=8.77$.

NOTE.—Wire ignitor burned through; ignition lasted 15 minutes; 14.5 liters of hydrogen used.

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TABLE 6.—*Data from mixed 2 to 4 and 40 to 60 mesh coal 3¾ inches thick; calculated proportion of voids in mixture, 19.3 per cent; placed in lower compartment, 9059 grams of 2 to 4 mesh coal and 3,432 grams of 40 to 60 mesh coal.*

EXPERIMENT 6A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
—0.23					0.00
— .09					1.00
+ .06					2.00
.23					3.00
.41					4.00
.55	1	20.19	4.15	24.34	
.62					5.00
.86					6.00
1.08	2	18.15	6.95	25.10	
1.14					7.00
1.47					8.00
1.70	3	16.44	8.66	25.10	
1.88					9.00
2.43					10.00
2.66	4	19.80	10.35	25.15	
3.23					11.00
3.42	5		11.42		
3.84					11.50
4.38	6	13.54	11.78	25.32	
4.80	7	13.41	11.99	25.40	12.00
5.85					12.30
6.02	8	13.13	12.36	25.49	
6.85	9	13.00	12.50	25.50	
7.28					12.50

K was evaluated with analysis No. 4. Equation, $t=5.17-3.92 \log_{10}(23.88-1.887y)$. K=3.92.

NOTE.—Ignition lasted 20 minutes; wire burned; 19 liters of hydrogen used. Small leak in lower compartment caused a steady increase in sum of oxygen in top and bottom.

EXPERIMENT 6B.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.83					0.00
1.03					1.00
1.20					2.00
1.23	1	19.80	1.35	21.15	
1.40					3.00
1.62					4.00
1.68	2	18.23	4.43	22.66	
1.86					5.00
2.15					6.00
2.23	3		6.25		
2.51					7.00
2.78	4	15.21	7.62	22.83	
2.95					8.00
3.40	5	14.20	8.79	22.99	
3.54					9.00
4.46					10.00
5.22					10.50
6.58					11.00
8.77					11.30

K was evaluated with analysis No. 5. Equation, $t=6.09-3.95 \log_{10}(20.92-1.834y)$. K=3.95.

NOTE.—There was a small leak in the lower compartment.

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TABLE 7.—*Data from 4 to 10 mesh coal, 5¾ inches thick; proportion of voids, 43.6 per cent; coal placed in lower compartment, 4,720 kg.*

EXPERIMENT 7A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.80					0.00
0.91					1.00
1.04					2.00
1.17					3.00
1.32					4.00
1.35	1	19.50	3.74	23.24	
1.49					5.00
1.68					6.00
1.88	2	17.52	6.98	24.50	
1.91					7.00
2.18					8.00
2.28	3	16.08	8.31	24.38	
2.53					9.00
2.67	4	15.20	9.34	24.54	
3.00					10.00
3.65	5	13.79	10.92	24.71	
3.74					11.00
4.07	6	13.40	11.31	24.71	
4.38					11.50
5.58					12.00
6.33	7	12.67	12.28	24.95	
6.91					12.20

K was evaluated with analysis No. 4. Equation, $t=4.86-3.03 \log_{10}(21.81-1.770y)$. K=3.03.

NOTE.—Seventh analysis not used in calculating; small leak in lower compartment.

EXPERIMENT 7B.

0.90					0.00
1.01					1.00
1.13					2.00
1.25					3.00
1.38	1	20.24	2.94	23.18	
1.39					4.00
1.55					5.00
1.73					6.00
1.92	2	18.19	7.22	25.41	
1.94					7.00
2.18					8.00
2.28	3	17.07	8.48	25.55	
2.49					9.00
2.72	4	15.95	9.66	25.61	
2.83					10.00
3.15	5	15.17	10.54	25.71	
3.44					11.00
4.43					12.00
4.57	6	13.77	12.13	25.90	
5.50					12.50
5.70	7	13.47	12.67	26.14	
6.46					12.70
6.77	8	13.24	12.92	26.16	

K was evaluated with analysis No. 5. Equation, $t=5.01-3.04 \log_{10}(22.42-1.739y)$. K=3.04.

NOTE.—Eighth analysis not used in calculations; small leak in lower compartment.

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TABLE 8.—*Data from mixed fines from storage piles, 8 inches thick, shaken down in apparatus, sample representing coal midway up side of storage piles of an industrial plant; proportion of voids, 33.4 per cent.*

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.19					0.00
0.36					1.00
0.54					2.00
0.74					3.00
0.96					4.00
1.21					5.00
1.27	1	19.91	4.42	24.33	
1.49					6.00
1.60	2	18.54	6.41	24.95	
1.83					7.00
2.10	3	17.22	7.71	24.93	
2.23					8.00
2.52	4	16.56	8.63	25.19	
2.73					9.00
2.97	5	15.82	9.44	25.26	
3.38					10.00
3.67	6	14.90	10.33	25.33	
4.36					11.00
5.12					11.50
5.57	7	13.73	11.73	25.46	
6.32	8	13.44	11.97	25.41	
6.33					12.00
7.14					12.20
7.37	9	13.21	12.28	25.49	
8.52					12.40
9.87					12.50

K was evaluated with analysis No. 4. Equation, $t=6.61-4.66 \log_{10}(23.83-1.890y)$. K=4.66.

EXPERIMENT 8B.

0.74					0.00
0.92					1.00
1.12					2.00
1.33					3.00
1.35	1	20.25	1.74	21.99	
1.58					4.00
1.78	2	19.14	4.60	23.74	
1.86					5.00
2.17					6.00
2.25	3	17.77	6.10	23.87	
2.50					7.00
2.65	4	16.84	7.22	24.06	
3.01					8.00
3.03	5	16.11	8.04	24.15	
3.60					9.00
4.37	6	14.30	9.86	24.16	
4.44					10.00
5.03					10.50
5.85					11.00
6.07	7	13.16	11.02	24.18	
7.17	8	12.78	11.42	24.20	
7.25					11.50
8.25					11.70
9.02					11.80
10.26					11.90
13.80					12.00

K was evaluated with analysis No. 4. Equation, $t=7.12-4.78 \log_{10}(21.63-1.799y)$. K=4.78.

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TABLE 9.—*Data from mixed large coal from storage piles, 8 inches thick, sample representing coal from bottom of storage piles of an industrial plant; proportion of voids, 43.9 per cent.*

EXPERIMENT 9A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.60					0.00
0.75					1.00
0.91					2.00
1.09					3.00
1.25	1	19.70	2.76	22.46	
1.29					4.00
1.52					5.00
1.70	2	18.15	5.68	23.83	
1.78					6.00
2.07	3	16.82	6.82	23.64	
2.10					7.00
2.42	4	16.00	7.84	23.84	
2.49					8.00
2.85	5	15.02	8.76	23.78	
2.99					9.00
3.63	6	13.92	9.78	23.70	
3.71					10.00
4.01					10.30
4.37					10.60
4.47	7	13.01	10.66	23.67	
4.66					10.80
5.01					11.00
5.45					11.20
5.55	8	12.42	11.25	23.67	
6.07					11.40
6.47					11.50
7.03					11.60
7.22	9	12.01	11.62	23.63	
7.88					11.70
7.51					11.80

K was evaluated with analysis No. 4. Equation, $t=5.80-3.87 \log_{10}(22.80-1.862y)$. K=3.87.

EXPERIMENT 9B.

0.66					0.00
0.80					1.00
0.95					2.00
1.13					3.00
1.22	1	19.63	3.37	23.00	
1.32					4.00
1.55					5.00
1.63	2	17.91	5.48	23.39	
1.80					6.00
2.00	3	16.65	6.74	23.39	
2.10					7.00
2.37	4	15.78	7.72	23.50	
2.48					8.00
2.98	5	14.46	8.98	23.44	
3.31					9.00
3.71					9.50
4.02					10.00
4.20	6	12.92	10.49	23.41	
4.40					10.30
4.71					10.60
5.11					10.80
5.18	7	12.31	11.08	23.39	
5.63					11.00
6.42					11.20
7.05					11.40
7.18	8	11.81	11.54	23.35	
8.04					11.50
11.85					11.60
					11.70

K was evaluated with analysis No. 4. Equation, $t=5.63-3.66 \log_{10}(22.88-1.950y)$. K=3.66.

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TABLE 10.—*Data from mixed fines from storage piles, 8 inches thick, not shaken down in apparatus; proportion of voids, 36.9 per cent.*

EXPERIMENT 10A.

Time (hours).	Analysis No.	Percentage of O_2 found in bottom.	Percentage of O_2 found in top.	Sum of O_2 in top and bottom.	Percentage of O_2 (calculated) in top.
0.79					0.00
0.98					1.00
1.18					2.00
1.33	1	20.13	1.27	21.40	
1.40					3.00
1.65					4.00
1.73	2	19.08	4.34	23.42	
1.94					5.00
2.19	3	17.62	5.80	23.42	
2.26					6.00
2.57	4	16.70	6.79	23.49	
2.66					7.00
2.93	5	15.96	7.60	23.56	
3.14					8.00
3.59	6	14.88	8.76	23.64	
3.88					9.00
4.59	7	13.76	9.88	23.64	
4.70					10.00
5.09					10.30
5.56					10.60
5.87	8	12.92	10.77	23.69	
5.94					10.80
6.40					11.00
7.02					11.20
7.17	9	12.43	11.26	23.69	
7.90					11.40
9.46					11.60
11.16					11.70

K was evaluated with analysis No. 4. Equation, $t=7.10-4.76 \log_{10}(21.13-1.794\,y)$. K=4.76.

EXPERIMENT 10B.

0.74					0.00
0.93					1.00
1.15					2.00
1.27	1	19.90	1.40	21.30	
1.38					3.00
1.64					4.00
1.70	2	18.90	4.12	23.02	
1.95					5.00
2.10	3	17.66	5.46	23.12	
2.30					6.00
2.53	4	16.67	6.57	23.24	
2.72					7.00
2.98	5	15.64	7.51	23.15	
3.24					8.00
3.56					8.50
3.84					9.00
4.39					9.50
4.42	6	13.73	9.52	23.25	
4.97					10.00
5.26					10.20
5.59					10.40
5.67	7	12.86	10.44	23.30	
5.98					10.60
6.46					10.80
7.07					11.00
7.10	8	12.30	11.02	23.32	
7.48					11.10
7.95					11.20
8.57					11.30
9.43					11.40
10.91					11.50
∞					11.60

K was evaluated with analysis No. 4. Equation, $t=7.25-4.92 \log_{10}(21.04-1.814\,y)$. K=4.92.

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TABLE 11.—*Summary of data from tests.*

Experiment No.	Size of coal, meshes per inch.	Percentage of voids.	Depth of coal layer (inches).	K—decimal hours.	K calculated for 8 inches of depth.	Product of percentage of voids and K for 8 inches of depth.
1A	40 to 60	46.5	8	4.05	.....	188.4
1B	40 to 60	46.5	8	4.01	.....	186.5
2A	4 to 10	43.6	8	4.11	.....	179.1
2B	4 to 10	43.6	8	4.14	.....	180.5
2C	4 to 10	43.6	8	4.18	.....	182.2
3A	2 to 4	41.5	8	4.19	.....	174.6
3B	2 to 4	41.5	8	4.11	.....	170.0
4A	1 to 2 [a]	45.3	8	3.93	.....	178.0
4B	1 to 2 [a]	45.3	8	3.79	.....	171.7
5A	2 to 4 / 40 to 60	19.3	8	8.54	.....	164.8
5B	2 to 4 / 40 to 60	19.3	8	8.77	.....	169.3
6A	2 to 4 / 40 to 60	19.3	3¾	3.92	8.36	.....
6B	2 to 4 / 40 to 60	19.3	3¾	3.95	8.42	.....
7A	4 to 10	43.6	5⅓	3.03	4.22	.....
7B	4 to 10	43.6	5⅓	3.04	4.23	.....
8A	Storage pile, fines shaken down.	33.4	8	4.66	.....	155.6
8B	Storage pile, fines shaken down.	33.4	8	4.78	.....	159.7
9A	Storage pile, large, not shaken down.	43.9	8	3.87	.....	169.9
9B	Storage pile, large, not shaken down.	43.9	8	3.66	.....	160.6
10A	Storage pile, fines not shaken down	36.9	8	4.76	.....	175.6
10B	Storage pile, fines not shaken down	36.9	8	4.92	.....	181.5

[a] Inches.

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